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Determining the sustainability of large-scale photovoltaic solar power plants

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ABSTRACT

This paper highlights an evaluation of the potential level and nature of sustainability for large-scale photovoltaic (PV) solar power plants. This was achieved by applying a mathematical model of sustainability to the results of a qualitative-based environmental impact evaluation of the installation and operation of large-scale solar power plants.

The results from the model application indicated that large-scale PV solar power plants were conducive to achieving strong sustainability. This was because of the significant environmental benefits derived from PV solar power plants in respect to its construction and operation, as well as the minimum impacts derived from anthropogenic sources. This paper however notes that PV solar technology requires significant improvements in the conversion of sunlight to electric energy. This paper concludes that PV solar power plants offer a potentially significant and sustainable source of energy.

Contents

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1. Introduction

1.1. Purpose of paper

This paper continues our previous work on the quantitative evaluation of the sustainability and unsustainability of renewable energy by the application of a mathematical model. The mathematical model of sustainability and its application were first highlighted in respect to geothermal energy [1]. In this paper, we turn our focus to solar energy, and the sustainability of the installation and operation of large-scale photovoltaic (PV) solar power plants. This is based upon the work of Turney and Fthenakis [2]. In their paper, they conducted a qualitative-based assessment of the impacts derived from installing and operating large-scale PV solar power plants in the United States of America (U.S.A.). This was based on a comparison to traditional sources of electricity generation.

In this paper, we develop a quantitative scale to convert their original results into an appropriate numerical value for each category assessed. We then adopt these values to apply the model to determine, if appropriate, the level and nature of sustainability of large-scale PV solar power plants. The results should provide an indication as to whether large-scale PV solar power plants can be considered as sustainable or unsustainable.

1.2. The energy problem

During the last few decades, significant levels of demand for energy have become an increasing source of concern. This is because energy is essential to both socio-economic development and improving the quality of life in all countries [3]. The increased use of fossil fuels and other natural resources, on which humanity relies for their own survival and well-being, is the associated consequence of impacts upon the environment, specifically through damage to the air, climate, water, land and wildlife [4]. Consequently, if current energy approaches are considered as unsustainable in respect to environmental, economic and social considerations, then viable alternatives are required to meet the current and future global demand for energy. Because of the seriousness of the potential threat posed by global environmental change, strongly inferred to be predominantly anthropogenically induced, there is an increasing stress upon traditional sources of energy against the backdrop of increasing global demand, which has caused the pursuit of renewable sources of energy generation.

In the year 2000, renewable energy (e.g. biomass, hydroelectric, solar, wave, tidal, and wind) accounted for 14% of the current total global energy demand [5]. Renewable sources of energy are expected to increase significantly as humans attempt to avert the potentially catastrophic effects of global environmental change. According to Fridleifsson [6], energy generated by renewable sources is expected to significantly rise to 30–80% by 2100. Kralova and Sjobolm [7] highlighted significant increases to the use of global renewable energy by 2040 in their modelled scenario. This scenario in respect to energy consumption from solar energy technologies, all renewable sources, and all energy sources is shown in Fig. 1. Of all of the energy alternatives that have been suggested in the literature as a viable mass generation source of renewable energy, solar energy is repeatedly considered as such a source.

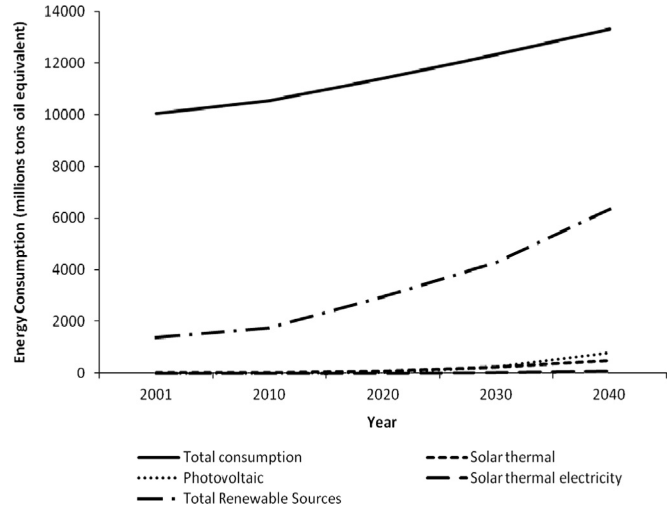

Fig. 1. Global renewable energy scenarios by 2040, *after* Kralova and Sjobolm [7], with specific focus on consumption from solar energy technologies compared to total consumption from all renewable sources and overall total energy consumption (renewable and non-renewable).

1.3. Sustainability and solar energy

1.3.1. Sustainable development and energy

Sustainable development has entered into the conscience of humanity during the last 25 years. The most well-known definition was stated by the World Commission on Environment and Development (WCED) which defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [8]. However, when the literature cites this definition, the two associated caveats are often not stated in conjunction with the WCED's definition. The two caveats are both concerned with the limitations and ability of the environment to meet present and future needs in respect to the following: (1) The state of technology and (2) the social organisation [8]. These caveats and the definition provided were intended to address the concern at the time of the increasing needs of developing countries, such as India and China. This concern was in respect of such countries utilising their natural resources at a significantly increasing rate to achieve economic development, *or* developing countries where resources were limited and/or near to exhaustion against the backdrop of excessively rising populations and famine. So whilst the WCED report did engender a new spirit of global environmental conscience and action, there has been a growing concern that the goals of sustainable development to achieve a balanced approach towards environment, social and economic outcomes have been compromised [9].

The development of sustainable energy is one of the biggest challenges for humanity in the 21st century [10,11]. The significant economic expansion that has occurred since the Industrial Revolution has been strongly related to the use and production of energy [12]. The use of fossil fuels as the source of energy has driven this expansion [12]. However, as the IPCC [13] reported, this in turn has caused large-scale rises in emissions of greenhouse gases. As a direct consequence, this has caused significant environmental and economic impacts through climate change [13].

Therefore, the issue is how to produce cleaner and sustainable sources of energy for the future, particularly in rapidly economically expanding economies such as China and India, where the demand for energy currently is the greatest [12]. In part, this demand is greater in such countries because of their high levels of population and the consequential increasing expectations for improved living standards and quality of life. Consequently, finding clean and significant energy sources that are renewable has become an imperative and it is as one of the goals to achieve sustainable development. It was for this reason that research into developing solar energy as a mass source of energy generation has gathered pace.

Recently, Borenstein [14] has highlighted the significant economic barriers currently to the use of renewable sources of energy. The key potential economic barriers to the greater adoption of energy production from solar (as well as wind and biomass) are three-fold: (1) the cost of generation; (2) the cost of power transmission to meet the demand; and (3) the value of the power which is generated. The use of rooftop solar PV panels does reduce the necessity to commit significant resources to high voltage transmission lines [14]. However, as Borenstein [14] points out, there is a considerable debate as to whether the use of such panels actually reduces or increases the cost of the local distribution network.

1.3.2. The impacts of solar energy

Solar energy, as portrayed in the literature, is considered as environmentally and socio-economically beneficial. The positive impacts (environmental and socio-economic) of solar energy are considered as the following [4,15–17]:

- reductions in emissions of greenhouse gases and toxic gases;
- reclamation of degraded land;
- reduced transmission lines from the electricity grids;
- improved quality of water resources;
- increased energy interdependence at the regional and/or national level;
- energy diversification and security;
- improved employment opportunities;
- rapid electrification in the rural areas of developing countries; and
- supporting deregulation of energy markets.

However, there some negative impacts (environmental and socio-economic) associated with solar energy, as noted by Tsoutsos et al. [4]:

- solar power plants tend to be site specific, depending on the size and scope of the project;
- loss of visual amenity;
- loss of cultivable land and other economically valuable land use;
- impact on ecosystems, particularly in the case of large PV schemes;
- accidental release of chemicals into the local environment; and
- occupational hazards during construction and operation.

However, with proper design, planning, siting and management, as Tsoutsos et al. [4] observes, these negative impacts can be properly mitigated and even avoided.

1.3.3. Sustainability issues with PV systems

In the case of PV systems, there are potentially significant issues for their long-term sustainability credentials. Fthenakis [18] observes that PV systems would be inherently sustainable unless they become too expensive to produce; the materials required for their manufacture become depleted; *or* they are deemed environmentally unsafe. The key issue here is the fact that PV systems require highly specialised natural resources such as thin-film silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) [18]. This raises legitimate questions as to the extraction and production of such materials. The most significant impacts of PV systems is in the obtaining and processing of the raw materials required through the mining of the metals and other resources. Mining is considered to be extremely impactful both environmentally and socially, whilst being economically beneficial to the local area. Despite these concerns, PV technology is considered as capable of fulfilling sustainable electricity needs [19].

1.3.4. Assessing sustainability of solar energy

The assessment of the sustainability of renewable energy technology and generation has been conducted through various means within the literature. These approaches have been conducted, within the context of impact assessment, either through quantitative or qualitative means. The Institute of Environmental Management and Assessment (IEMA) states that quantitative techniques usually involve a rigid method being set out and followed, whereas qualitative techniques typically depend upon professional judgement [20]. The literature is abundant with various assessments of the 'sustainability' of renewable energy options. It is unwise for this paper to detail every paper or trend in the subject. Instead, a few papers do highlight the general approach and options adopted to evaluate sustainability of renewable technology and generation.

1.3.4.1. Life cycle assessment/analysis (LCA). The most favoured approach to sustainability assessment is Life Cycle Assessment/Analysis (LCA). LCA is a technique which assesses the environmental impacts related to product or development from the extraction of the raw material(s) through to the processing, production, supply, operation, repair and maintenance, and the final disposal, recycling or closure – an approach known as the cradle-to-grave approach. LCA is favoured due to its international recognition through ISO 14040 and 14044 guidelines [21,22] and the cradle-to-grave approach to the analysis of impacts. There have been numerous papers and studies which have adopted a LCA approach to the evaluation of the sustainability of renewable energy generation and technology. These include Santoyo-Castelazo et al. [23]; Thornley et al. [24]; Laleman et al. [25]; and Sengul and Theis [26].

1.3.4.2. Indicators. Indicators are a very much favoured approach as well in determining the sustainability of a process or product. Indicators, within the context of environment–human system, are numerical values which provide quantitative measures as to the state of, or impacts upon, specific parameters of the environment and/or human health. Indicators can be monitored over time and at a wide variety of geographical scales from local to international levels. Evans et al. [27] adopted such an approach when evaluating various renewable energy technologies in respect to the following indicators: (1) price of electricity generation; (2) greenhouse gas emissions; (3) availability and limitations of technology; (4) energy generation efficiency; (5) land use; (6) water consumption; and (7) social impacts. On the other hand, Chatzimouratidis and Pilavachi [28] used a system analysis approach called the Analytic Hierarchy Process (AHP) [29–32] as a conduit for performing a multi-criteria analysis of the sustainability of various power plants, either from non-renewable or renewable sources of energy. The AHP creates a hierarchical tree where all of the criteria and sub-criteria are stated according to their importance, and then weighted as appropriate.

1.3.4.3. Geographical information system (GIS). GIS has become a very popular tool to evaluate the sustainability of energy generation options. GIS, very simply, is a system which presents all types of geographical data through its capture, storage, manipulation, analysis, and management. In recent years, the significant technological improvements in computer hardware and software have made GIS, as an assessment method, an extremely powerful approach. Yue and Wang [33] highlighted the usefulness of GIS in respect to an evaluation of the potential for sources of renewable energy in the Chigu area of south-western Taiwan. Through the input of relevant

local conditions in regards to the environment–human system, it was possible for them to evaluate the best options and locations for renewable energy generation.

1.3.4.4. Multi-criteria assessment (MCA). MCA involves a range of decision-making techniques which contain different criteria in order to come to a final decision as to the merits or demerits of a project or development. MCA's main purpose is the consistent management of large amounts of complex information, typically, through the use of weighted and/or scored matrices. This, as a result, requires the development of measurable quantitative or qualitative criteria in order to evaluate whether any, some or all of the stated objectives would be achieved.

Afgan and Carvalho [34–36] and Afgan et al. [37] have conducted the most impactful work on the sustainability assessment of renewable energy generation. This was in respect to the original work of Afgan and Carvalho [34] in the development and application of a multi-criteria assessment for new and renewable technologies. This assessment was based on the decision making procedure highlighted by Hovanov et al. [38], Hovanov and Hovanov [39], Gal and Hanne [40], Climaco [41] and Fishburn [42]. The assessment, as Afgan and Carvalho [34] stated, reflects the consideration of all of the criteria evaluated, and is expressed by a General Index of Sustainability. The multi-criteria assessment, as developed by Afgan and Carvalho [34], has been applied to evaluating the sustainability of hydrogen energy systems [33,35] and hybrid energy systems [34]. The latter includes solar technology as part of two of the hybrid options evaluated.

1.3.4.5. Environmental impact assessment (EIA). EIA is a process which adopts a systematic analysis of the environmental (and human health and well-being) consequences of a potential or actual project, procedure, policy or proposals, and communicates measures for the prevention and/or management of impacts. The methodology adopted by Turney and Fthenakis [2] is consistent for it to be considered as an EIA based method on the stated definition given.

There is considerable literature concerning the inferred use of EIA as a mechanism to evaluating sustainability, as noted by Abdel Wahaab [43], Glasson et al. [44], Lawrence [45] and Pope et al. [46]. In a recent paper [47], we proposed a geocybernetic relationship between EIA and sustainability. This was intended to develop a potential formalisation of the relationship and use of EIA as a mechanism for evaluating sustainability. This paper achieved this through the use of the five fundamental geocybernetic paradigms, as developed by Schellnhuber [48–50]. This, along with the other considerable literature on the subject, emphasizes the strong bond between EIA and sustainability, and the viability to determine sustainability from an EIA.

1.4. Paper structure and potential outcomes

This paper will utilise an assessment of the environmental and human impacts of solar power plants as a basis to determine sustainability. However, an appropriate approach to evaluate sustainability from impact-based assessment must be in place. Consequently, we intend to apply a mathematical model of sustainability [51,53] to the results of Turney and Fthenakis [2].

This paper will first outline the original methodology of Turney and Fthenakis [2] in evaluating the environmental impacts of large-scale solar power plants. Then this paper will describe the development of an appropriate and representative numerical framework to the qualitative-based results of Turney and Fthenakis [2]. Finally, using the quantitative-based results obtained, this paper will then apply the model to evaluate whether solar power plants are sustainable or unsustainable, and if deemed as sustainable, determine the level and nature of sustainability. The results obtained may offer tangible insights as to the credence of the beliefs concerning the sustainability of solar power as a potential energy source.

2. Methodology

2.1. Original methodology – Turney and Fthenakis (2011)

Turney and Fthenakis [2] in their paper on the environmental impacts of large solar power plants evaluated 32 impacts in total. This was in relation to the installation and operation of such plants. The impacts were categorised by Turney and Fthenakis [2] into the following sub-sections: land use; human health and well-being; wildlife and habitat; geohydrological resources; and climate and greenhouse gases. Each of the impacts was evaluated in respect to the following:

i. Description of the physical effect derived, compared to traditional U.S. power generation (coal, oil, natural gas, nuclear, hydro, and other renewable).
ii. The nature of the impact, compared to traditional U.S. power generation, was determined to be beneficial, detrimental, or neutral. If no suitable data was available to make a determination, then the impact was evaluated as unknown.
iii. The priority of the impact was evaluated – this was either deemed as low, moderate or high.

In respect to the priority of impacts, this was based on the U.S. National Environmental Protection, 40 CFR 1508.27 [52] definition of (impact) significance [2]. This meant that the impact priority was evaluated, in order of mitigation requirements, as one of the following by Turney and Fthenakis [2]:

- *Low* – where the project does not require any mitigation before commencing.
- *Moderate* – where mitigation is necessary and can be done at a low cost, or can be left semi-mitigated.
- *High* – where mitigation is both costly and needs to be fully completed.

2.2. Model application

2.2.1. Overview

This paper is based on research which is developing further applications of a mathematical model of sustainability to assessments of projects or developments. The model and its application are highlighted and detailed in our previous papers [1,51,53–56]. This paper represents a furthering of the model's application in regards to a qualitative environmental assessment of large-scale solar power plants. Consequently, this research has required developing a suitable numerical scale to, as fairly as possible, reflect and represent the original results of Turney and Fthenakis [2]. From this, using the model's application methodology originally developed in our PhD [53], we made appropriate minor adjustments and applied the application methodology (Fig. 2).

2.2.2. Quantification of original results

The application of any mathematical model or equation(s) requires numbers. Because Turney and Fthenakis [2] adopted a qualitative approach to impact assessment – a word-based evaluation, then their

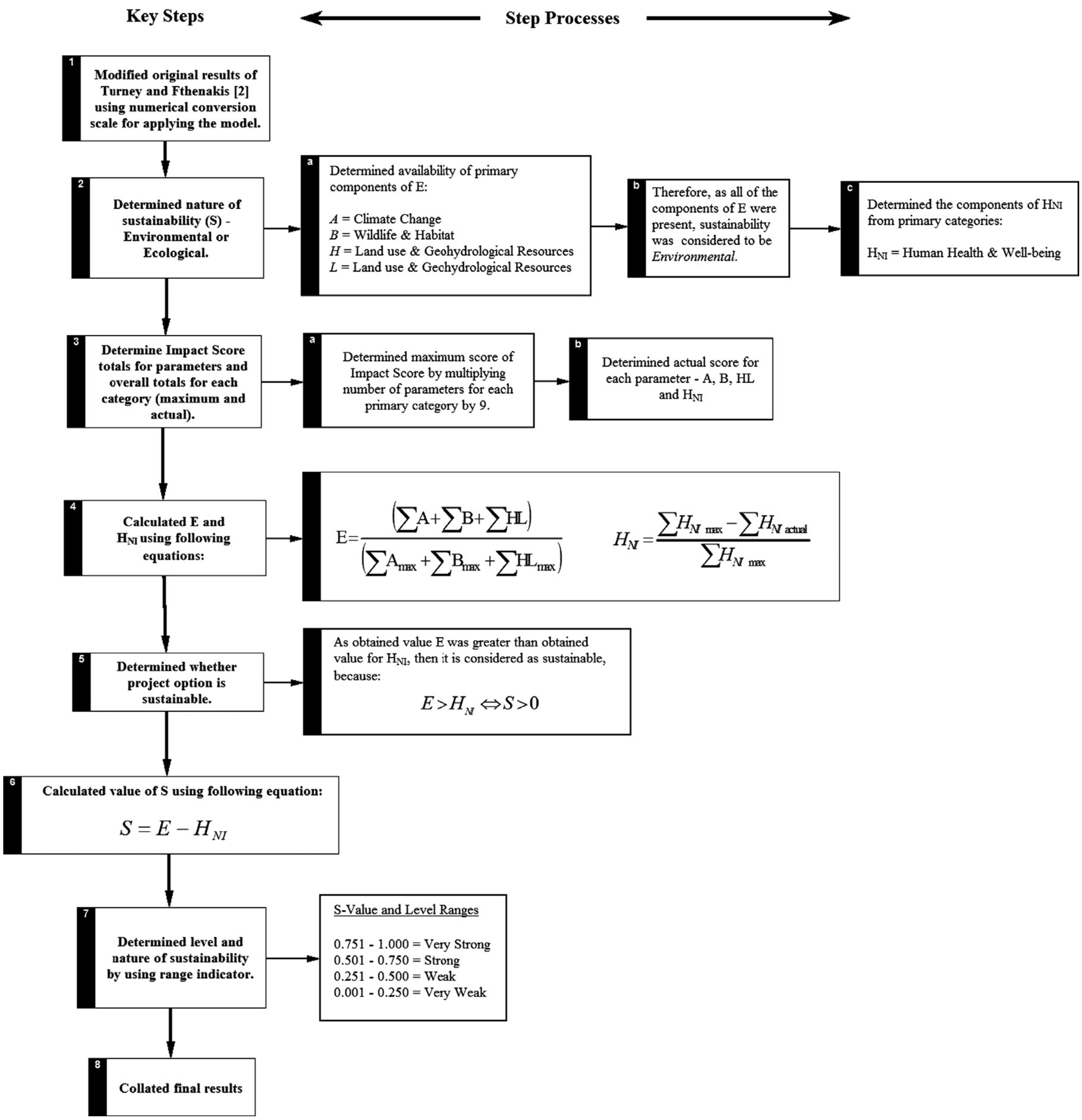

Fig. 2. A simplified process diagram of the application methodology adopted to apply the mathematical model of sustainability [53,54], based on previous applications of the model to various quantitative-based assessments of projects/developments [1,51,53–56].

assessment criteria needed to be converted into a numerical scale in order to use the model. Therefore, based on the structure of the methodology adopted by Turney and Fthenakis [2], we organised their impact type and priority in order of best to worst. We then decided to use a simple 1–9 scale to reflect the type and priority of impacts, as shown in Table 1. The 1–9 scale was decided as the appropriate mechanism for the following two key reasons:

(i) A scale adopting positive and negative values could have been used to clearly denote beneficial or detrimental impacts, and this was strongly considered. However, it was decided not to use this approach due to the potential of a negative total value from any of the primary categories. This was because a process similar to that utilised and discussed in our geothermal paper [see: 1] would be required. It would involve adding an appropriate positive number to obtain a 'relative score' for each parameter total. So therefore, a simpler and more direct approach was desired.

(ii) In respect to model application, the 1–9 scale allows for a more manageable process to determine the maximum and actual scores of each of the designated categories, as used in the model.

Using Table 1, the original results of Turney and Fthenakis [2] (Table 2) were quantified, and are shown in Table 3.

2.2.3. *Model application methodology*

Based on our previous applications of the model [1,51,53,55,56] which have extensively detailed the application process, Fig. 2 shows a simplified process diagram of the model's application to the quantified results of Turney and Fthenakis [2] shown in Table 3. The model's terminology, in respect to Fig. 2, is as follows:

S = Sustainability (Environmental)
E = (the) Environment
$\mathbf{H_{NI}}$ = Human Needs and Interests
A = Atmosphere
B = Biosphere
HL = Hydrosphere and Lithosphere
t = time

Due to Turney and Fthenakis's [2] category of land use and geohydrological resources, this required a minor change to the application of the model from previous instances. Usually land use and geohydrological resources would be categorised as lithosphere (L) and hydrosphere (H) separately and respectively. Because of the combined category, we therefore made a slight amendment to the model's application to reflect this combined category. Therefore, instead of ΣH and ΣL and the equivalent notations for the maximum potential total – i.e. $\Sigma H_{\max}$, we utilise a combined notation of ΣHL and $\Sigma HL_{\max}$. This causes no conflict within the model as the environment (**E**) is defined as $\mathbf{E}(t)=(A+B+H+L)$ [1,51,53–56]. Therefore, as there was a combined category which contains at least two of the primary categories of **E** is present, then it is prudent to reflect this in the model application process. Consequently, in the case of this paper, the following is true (adapted from [1,51,53–56]):

$$\mathbf{E}(t)=(A+B+HL)\equiv(A+B+H+L) \quad (1)$$

Table 1
The conversion table for the qualitative evaluation of the nature and priority of impacts conducted by Turney and Fthenakis [2] to an appropriate numerical value in order to apply the mathematical model of sustainability [53,54].

Impact state	Impact priority	Relative score (Model)
Beneficial	Low	9
Beneficial	Moderate	8
Beneficial	High	7
Neutral/Unknown	Low	6
Neutral/Unknown	Moderate	5
Neutral/Unknown	High	4
Detrimental	Low	3
Detrimental	Moderate	2
Detrimental	High	1

3. Calculations and results

The original results of Turney and Fthenakis [2] and the conversion into a representative semi-quantitative result to be

Table 2
A summary of the original results of Turney and Fthenakis [2] of the nature and priority of environmental impacts of large-scale solar power plants, compared to traditional U.S. energy generation (Reproduced with very kind permission).

Impact category		Impact state	Impact priority
Human health and well-being	*Exposure to hazardous chemicals*		
	Emissions of mercury	Beneficial	Moderate
	Emissions of cadmium	Beneficial	High
	Emissions of other toxics	Beneficial	Moderate
	Emissions of particulates	Beneficial	Low
	Other impacts		
	Noise	Beneficial	Low
	Recreational resources	Beneficial	Moderate
	Visual aesthetics	Neutral	Moderate
	Climate change	Beneficial	High
	Land occupation	Neutral	Moderate
Wildlife and habitat	*Exposure to hazardous chemicals*		
	Acid rain: SO, NO_x	Beneficial	Moderate
	Nitrogen: eutrophication	Beneficial	Moderate
	Mercury	Beneficial	Moderate
	Other: e.g. cadmium, lead, particulates	Beneficial	High
	Physical dangersm		
	Cooling water intake hazards	Beneficial	Moderate
	Birds: flight hazards	Detrimental	Low
	Roadway and railway hazard	Beneficial	Low
	Habitat		
	Habitat fragmentation	Neutral	Moderate
	Local habitat quality	Beneficial	Moderate
	Land transformation	Neutral	Moderate
	Climate change	Beneficial	High
Land use and geohydrological resources	*Soil erosion*		
	During construction	Beneficial	Low
	During routine operation	Unknown	Moderate
	Surface water runoff		
	Water quality	Beneficial	Moderate
	Hydrograph timing	Unknown	Low
	Waste management		
	Fossil fuel waste spills	Beneficial	Moderate
	Nuclear waste stream	Beneficial	High
	Groundwater		
	Groundwater recharge	Unknown	Moderate
	Water purity	Beneficial	Moderate
Climate change	*Global climate*		
	CO_2 emissions	Beneficial	High
	Other GHG emissions	Beneficial	High
	Change in surface albedo	Neutral	Low
	Local climate		
	Change in surface albedo	Unknown	Moderate
	Other surface energy flows	Unknown	Low

Table 3
The quantified results of Turney and Fthenakis [2] using Tables 1 and 2, in order to apply the mathematical model of sustainability [53,54].

Impact category		**Relative score**
	CO_2 emissions	7
Climate change	Other GHG emissions	7
	Change in surface albedo	6
(A)	Change in surface albedo	5
	Other surface energy flows	6
	Total score (max: 45) (ΣA)	**31**
	Acid rain: SO, NO_x	8
Wildlife and habitat	Nitrogen: eutrophication	8
	Mercury	8
(B)	Other: e.g. cadmium, lead, particulates	8
	Oil spills	7
	Cooling water intake hazards	8
	Birds: flight hazards	3
	Roadway and railway hazard	9
	Habitat fragmentation	5
	Local habitat quality	8
	Land transformation	5
	Climate change	7
	Total score (max: 108) (ΣB)	**84**
	During construction	9
Land use and geohydrological resources	During routine operation	5
	Water quality	8
	Hydrograph timing	6
(HL)	Fossil fuel waste spills	8
	Nuclear waste stream	7
	Groundwater recharge	5
	Water purity	8
	Total score (max: 72) (ΣHL)	**56**
	Emissions of mercury	8
Human health and well-being	Emissions of cadmium	7
	Emissions of other toxics	8
($\mathbf{H_{NI}}$)	Emissions of particulates	9
	Noise	9
	Recreational resources	8
	Visual aesthetics	5
	Climate change	7
	Land occupation	5
	Total score (max: 81) ($\Sigma \mathbf{H_{NI}}$)	**66**

able to apply the model are shown in Tables 2 and 3 respectively. Through the application of the model described previously in the methodology and Fig. 2 respectively, the following calculation and result were obtained:

$$\mathbf{E} = \frac{(\sum A + \sum B + \sum HL)}{(\sum A_{\max} + \sum B_{\max} + \sum HL_{\max})}$$

$$\mathbf{E} = \frac{(31 + 84 + 56)}{(45 + 108 + 72)}$$

$$\mathbf{E} = 0.760$$

$$\mathbf{H_{NI}} = \frac{(\sum \mathbf{H_{NI}}_{\max} - \sum \mathbf{H_{NI}})}{\sum \mathbf{H_{NI}}_{\max}}$$

$$\mathbf{H_{NI}} = \frac{(81-66)}{81}$$

$$\mathbf{H_{NI}} = 0.185$$

Therefore, as

$$\mathbf{E} = 0.760, \quad \mathbf{H_{NI}} = 0.185$$

$$\mathbf{E} \geq \mathbf{H_{NI}} \Leftrightarrow \mathbf{S} \geq 0$$

Sustainability occurring. So therefore:

$$\mathbf{S} = \mathbf{E} - \mathbf{H_{NI}}$$

$$\mathbf{S} = 0.760 - 0.185$$

$$\mathbf{S} = 0.575 \Rightarrow \text{Strong sustainability}$$

The results would indicate that the installation and operation of a large-scale PV solar power plant would be conducive to achieving strong sustainability. The reasons for this shall now be explored further.

4. Discussion

The results indicate that an **S**-value of 0.575 was obtained for the level of sustainability for large-scale PV solar power plants. This consequently infers that the nature of sustainability was considered to be strong. The level and nature of sustainability evaluated was based on the obtained **E**-value of 0.760 being greater than the obtained $\mathbf{H_{NI}}$-value of 0.185. The results would certainly seem to indicate and support the fundamental assertion that solar energy generation is inherently sustainable. This is based on the very high **E**-value obtained which indicates significant environmental benefits and minimum negative impacts to the environmental system at the spatial–temporal scales. Further, the $\mathbf{H_{NI}}$-value indicates minimum impacts from the anthropospheric system. This is important as in previous results obtained using the model, the obtained value of $\mathbf{H_{NI}}$ was a primary reason why sustainability failed to be achieved at a higher level or not at all. This is because of the significant impacts and feedbacks created by

anthropogenic activities upon the coupled environment–human system. Consequently, solar power may offer a viable and sustainable alternative to the exponential demand for energy globally. Based on the relative scores highlighted in Table 3, it is possible to suggest reasons as to why this may be the case.

In respect to the parameters in the atmosphere (*A*) category, the scores indicated that the primary benefit was the reduction of climate change-inducing mechanisms in the CO_2 and other GHG (Greenhouse Gases) emissions. However, the scores indicate that albedo and energy flows may be disrupted to some degree at the local and global level. On the one hand, this may have some impact in respect to the adequate dispersal of excessive heat and light energy that is a consequence of anthropogenically-induced climate change. On the other hand, the fact that such energy is being utilised as a source of electricity generation, and as a means to reduce further sources and emissions that cause climate change and pollution, may infer that this disruption of energy flows may be a price worth paying.

In respect to parameters within the biosphere (*B*) category, there are significant improvements. Specifically, this was in respect to the avoidance of the associated pollution aspects derived from the use of fossil fuels as an energy generation source. There are also indications that hazards in respect to cooling water and transportation are improved. There is also improved habitat quality due to improvements in cooling water and transportation, as well as the reduced pollution. However, there are some detrimental and/or neutral impacts. PV solar power plants have significant negative effects to birds as a flight hazard due to the nature of a solar panel surface. Furthermore, solar power plants do cause some interruption of local habitats when sited. Consequently, this involves some changes to the immediate vicinity where solar power plants are located to ensure the proper operation of the panels in order to track the Sun during the course of the year. Finally, the beneficial impacts of solar power plants upon local ecosystems and habitats extend to mitigating the causes and impacts of climate change. Overall, PV solar power plants do offer a viable approach to the minimisation of ecological impacts from energy generation.

In respect to the hydrosphere–lithosphere (*HL*) category, there are significant benefits of PV solar power plants compared to traditional sources. With regard to pollution issues, the scores for water quality, water purity, fossil fuel waste spills, and nuclear waste stream, all had scores between 7 and 9. This consequently indicates that PV solar power plants, unlike fossil fuel and nuclear fission, do not cause significant impacts upon the hydrosphere and/or the lithosphere. This also extends to the during construction parameter where there is minimum impacts due to the significant reduction in construction time and resources. However, there are potential issues in respect to groundwater recharge due to solar panels intercepting precipitation, and as a result, this would reduce hydrological infiltration and percolation in the substrata to the water table and groundwater storage. This is partly due to the lack of literature concerning the long-term impacts and benefits of operating PV solar power plants. Overall, the potential benefits do seem to outweigh the disbenefits. However, the results in this category do indicate that further work as to mitigation and monitoring of solar power plants' impacts is required, so as to identify potential risks to the hydrosphere and lithosphere components of the environmental system.

Finally, in respect to parameters in the Human Needs and Interests ($\mathbf{H_{NI}}$) category, the overall impacts were determined to be very beneficial. Reduced pollution, noise, and the consequential effects of climate change, as well as maintenance of recreational resources, all scores in the 7–9 range. However, land occupation and visual aesthetics both had scores of 5, inferring that there are perceived impacts to the economic and intrinsic value and use of the land. This is because of the reduced use of the land, particularly where economic factors are dominant. This is a reasonable concern given the current pressures for affordable homes, agriculture, hi-tech or new industries etc. In addition, there is the issue of visual intrusion of solar power plants in perceived areas of environmental beauty, and where people have chosen to reside because of the attractiveness of an area. This reduces the perceived intrinsic value and quality of life, as well as a potential fear of some economic loss to property values. Overall, the minimum negative impacts to humans within the environment–human system ensure that a greater value and level of sustainability is derived from a source of renewable energy.

4.1. Broader context

Based on the results obtained and the current literature, solar technology needs to overcome to three key issues to rightly fulfil its potential as a sustainable source of mass energy generation, which are

1. To become more effective and efficient in the conversion of light energy to electrical energy, due to significant areas of land in order to generate modest to reasonable levels of electricity.
2. In respect to developed or rapidly economically developed countries, it requires PV solar technology that generate energy on an equivalent or greater scale than current methods.
3. The fact that solar technology is not anticipated to meet the goal of a primary source of mass energy generation by 2040.

There is consequently little doubt that solar power offers a potentially significant and sustainable source of mass energy generation. However, it requires significant technological improvements in energy conversion and reducing the land lost and used for solar power plants, in order to ensure a coupled environment–human pathway to a sustainable energy future.

In respect to the broader context of this paper's potential value, we would consider this to be in respect to the following:

1. Applied a mathematical model of sustainability developed through an understanding of environmental–human system sustainability science theory to a qualitative-based assessment of PV systems.
2. Provided an indicated value as to the potential sustainability of PV systems through a quantitative approach, as opposed to a qualitative or judgement-based approach.
3. Placed the results within the context of their interactions and impacts (positive and negative) within the local environment–human systems, which is the proper context to evaluate sustainability.

It would however be fair to point out that the application of the model to the results of Turney and Fthenakis [2] provides an initial indication of the sustainability of PV systems. A robust EIA method, such as the Rapid Impact Assessment Matrix [57,58], or Battelle Environmental Evaluation System [59], or even a modified Folchi method [60], would have provided a more definitive understanding of the potential impacts (positive and negative) of PV system upon the local environment–human system. From this, the model can be applied with a greater degree of certainty to established methodologies based on previous work [1,51,53–56]. The qualitative assessment of the impacts (positive or negative) of renewable energy schemes, in general, highlights a fundamental problem with the proper evaluation of the sustainability of such schemes in the wider community. The lack of transparency and clear quantitative indications of the impacts, through established methodological frameworks just highlighted, only increases the

potential tensions between the developers and the local community when such schemes are proposed and constructed. Therefore, if renewable energy schemes are to be considered as credible within the local communities where they are sited, then a more consistent, transparent and rigid EIA methodology through a quantitative or semi-quantitative approach is required. From this, it would be more appropriate to adopt approaches to evaluate sustainability, such as the model utilized in this paper.

5. Conclusion

This paper has initially indicated that the installation and operation of large-scale PV solar power plants can be considered as sustainable at a strong level. However, this paper has highlighted the need for greater energy conversion from sunlight to electricity as a key concern. Nevertheless, the ongoing research with respect to this certainly shows that many consider solar power as a viable source of energy. If solar energy can be harnessed to its potential, then humans will have a permanent and unlimited supply of free and clean energy. This will be with minimum or no long-term environmental impact.

Therefore, the results indicated in this paper certainly initially support the presupposition in the literature as to the sustainability credentials of solar energy. However, as with our geothermal paper [1], this paper's potential contribution is to debate the actual sustainability of renewable energy. This is in regards to obtaining a calculated indicative value of the sustainability of solar power plants and its inferred nature, and was based upon an assessment of the environmental and human impacts. Furthermore, this paper developed a new quantitative mechanism to a qualitative-based assessment, in order to apply a mathematical model of sustainability [51,53]. However, a more robust EIA methodology to apply the model would have been preferable. Nevertheless, the initial results for an indicated value of the sustainability of large-scale PV systems does further debate as to the actual contribution of such systems towards sustainable development. To this end, this paper hopefully makes a further and useful contribution to the ongoing question of the long-term sustainability of the siting and operating of renewable energy facilities.

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